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100th Year 1988
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A Journal of Scottish Natural History

THE SCOTTISH NATURALIST

Founded 1871

A Journal of Scottish Natural History

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A Journal of Scottish Natural History

With which is incorporated *The Annals of Scottish Natural History* and *The Western Naturalist*

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The Scottish Naturalist and Journal of the Perthshire Society of Natural Science
1871

The Scottish Naturalist
1872-1891

The Annals of Scottish Natural History
1892-1911

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1912-1939, 1948-1957, 1961-1964

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EDITORIAL: ONE HUNDRED YEARS

One hundred and seventeen years ago Dr. Francis Buchanan White, of Perthshire, founded the *Scottish Naturalist,* the first number of which was published in January 1871. From then on the journal appeared without a break until 1939, being published quarterly until 1911 (with the exception of 1883, which had only two parts), monthly from 1912 until 1918, and eventually bi-monthly from 1919 until 1939.

Publication was suspended at the outbreak of the second world war, but recommenced in 1948, with the journal being published three times a year (except 1955, a single volume) until 1957, when financial difficulties caused a temporary suspension. It continued as a single annual part from 1961 to 1964, but after 1964 publication was again suspended. Financial difficulties, however, were nothing new for the journal, for as long ago as 1874 Dr. White was exhorting subscribers to pay their subscriptions promptly. Indeed, worry over possible financial embarrassment had caused the Perthshire Society of Natural Science to modify its sponsorship in 1877 and to seek a commercial publisher.

In 1972, however, the journal was restarted, with the support of the Renfrewshire Natural History Society, and has been a considerable success ever since. In 1983 the original name of the *Scottish Naturalist* was restored, and responsibility for future publication was undertaken by the Scottish Natural History Library. A substantial endowment fund was established, the supply of papers suitable for publication is steadily increasing, and the list of subscribers is rising every year, so the future of our national journal of Scottish natural history looks assured.

Since its foundation the journal has appeared under several different names, and a brief summary of the record of publication since 1871 is given on the inside back cover. This year (1988) is actually the 100th year of publication, but we plan no particular celebration, just a quiet satisfaction that the journal has achieved its centenary and looks so well set for the future. Nevertheless, we are certainly grateful for all the many expressions of goodwill and congratulations which have been received, from learned societies, libraries, other scientific publications, and loyal subscribers, from all over Scotland, the British Isles, Europe, and even North America and Australasia.

Heartened by this, next year, once our one hundred years of publication have been completed, we hope to include the previously promised short article setting out a brief history of the journal, which should be of interest to bibliographers, librarians, and indeed to all Scottish natural historians.

It is perhaps fitting that most of the contents of this centenary volume should concern Scotland's most famous natural history phenomenon - the Loch Ness Monster. This, however, is sheer coincidence, following on the joint symposium on the Loch Ness Monster, held in Edinburgh in July 1987 by the International Society of Cryptozoology and the Society for the History of Natural History, and implies no commitment by the Editors one way or the other.

The journal was published as an annual volume from 1972 to 1986, but two parts were issued in 1987, and this year, to accommodate all the papers read to the Loch Ness symposium, three parts of the journal will be published. We hope to see this continue, which should lead to the rapid publication of the steady flow of papers now being received. Moreover, new features, which we propose to introduce from next year, will include a summary of the contents of the publications of Scottish natural history societies (projected as long ago as the 1983 Editorial) and a regular list of new natural history books received by the Scottish Natural History Library.

Looking back over all the past volumes, it is clear that editing the *Scottish Naturalist* has always been an enjoyable task, albeit a labour of love, for the journal's Editors. We thank all our loyal supporters for their continued confidence, and express the fond hope that the second hundred years will prove to be every bit as interesting as the first.

DIET COMPOSITION AND STOMACH FULLNESS IN THREE-SPINED STICKLEBACKS FROM THREE SCOTTISH POPULATIONS

By A.A. UKEGBU and F.A. HUNTINGFORD
Department of Zoology,
University of Glasgow

Introduction

An extensive literature, reviewed by Wootton (1984), exists both on the quantity and on the quality of the diet of the Three-spined Stickleback *Gasterosteus aculeatus*. It is clear from this literature that while patterns of feeding are broadly similar, populations differ in the details of their diet. The majority of studies of the partially-plated freshwater ('leiurus') form of this species report copepods, Cladocera and ostracods to be the predominant prey types in the diet (e.g. Hynes 1950, Manzer 1976, Allen and Wootton 1984). There are reports of larger Crustacea, such as amphipods and isopods, being taken by the fully-plated, partially marine ('trachurus') form and by some populations of 'leiurus' fish (e.g. Hynes 1950, Larson 1976). Feeding habits also vary with season and gender. For example, stomach fullness is higher in breeding males than in breeding females, and in spring and early summer compared to winter levels (Manzer 1976, Allen and Wootton 1984). Copepods are the predominant prey type in spring and summer, being replaced by ephemeropteran larvae later in the summer (Allen and Wootton 1984). In some populations, stickleback eggs are a major prey item during the breeding season (Worgan and FitzGerald 1981). Size is also a determinant of diet, since small fish are unable to consume the relatively large prey which make up the bulk of the diet of larger sticklebacks (Hynes 1950, Greenbank and Nelson 1959, Manzer 1976). In this paper we describe briefly some additional information on diet and stomach fullness in male and female sticklebacks of different ages from three populations in south-west Scotland, collected and killed during a study of the age structure and growth rates.

Material and Methods

Between October 1983 and August 1984, monthly samples of twenty sticklebacks were collected from three sites in and around Glasgow. These sites, all urban streams, were the River Kelvin (4°8'W, 55°57'N; NS67), the River Luggie (4°10'W, 55°57'N; NS67) and the Aurs (or Brock) Burn (4°20'W, 55°48'N;

NS55). The fish were returned to the laboratory, killed immediately (by MS222 anaesthesia), measured and assigned to one of three size categories, namely <29mm, 30-45mm, and >46mm. They were then weighed, sexed on the basis of their gonadal structure, and had their stomachs dissected out. The fresh weight of the full stomach was taken to the nearest 0.1mg; the stomach was then sliced open longitudinally and the food contents were scraped out. All the food items in each stomach were identified, to the level of class or family. The various food items recorded were then assigned to one of the following categories: *Asellus* and *Gammarus*, copepods (mainly *Cyclops* spp.), dipteran larvae (mainly chironomids), molluscs, ephemeropterans, invertebrate eggs, stickleback eggs, and plant material. For the purpose of analysis of stomach contents, the number of stomachs containing at least one individual of each food category was expressed as a percentage of the sum of all stomachs containing food, i.e. the occurrence method described by Hyslop (1980).

After removing the food, the stomach was reweighed empty and the weight of its contents calculated by subtraction. The percentage of fish with empty stomachs in each sample was calculated. In addition, and following Allen (1982), an index of stomach fullness was calculated to allow for the fact that the amount of food a full stomach holds depends on the size of the fish concerned. Thus:

$$\text{Stomach Fullness Index} = \frac{\text{Weight of stomach contents}}{\text{Weight of stomach}} \times 100$$

Diet compositon was analysed using a Chi^2 test, and stomach fullness scores by a series of one way analyses of variance.

Results

Most fish had food in their stomachs (only about 9% were empty) and average stomach fullness level was 38%. Diet composition was broadly comparable in all the stomachs analysed (over 700), although the details varied with season, population, gender and age (see below). Taking all the fish together, the predominant prey type was *Asellus* (and occasionally *Gammarus*), which was found in 30% of all stomachs, followed by dipteran larvae (22%) and copepods. A number of other items were found in the diet regularly but at low frequencies; these included plant material (5%), molluscs and Ephemeroptera (4%), and invertebrate eggs (2%). Stickleback eggs made up a tiny fraction of the diet, and no Cladocera were found.

SEASONAL CHANGES

Stomach fullness varied significantly with season (Figure 1a; $p>0.01$), being at its lowest during the winter months, when the percentage of fish with empty stomachs was correspondingly high. Stomach fullness then increased sharply in the spring, fell slightly in both sexes during the breeding season, increased again in July and August as young of the year started to feed intensively and then declined again to winter levels.

These changes in stomach fullness were accompanied by changes in diet composition (Figure 1, b-f); the occurrence of *Asellus* (as well as plant material) was lowest during the summer months, when other kinds of prey in the form of copepods and dipteran larvae were found more frequently. Ephemeroptera were commonest in the spring and summer months, while molluscs (and the very occasional stickleback egg) were found predominantly in fish caught during the summer. Invertebrate eggs were found at low, but fairly constant, frequencies throughout the year.

POPULATION EFFECTS

The proportion of fish with empty stomachs was broadly comparable in the three populations, but in both sexes stomach fullness was lower in fish from the Aurs Burn than in those from the Rivers Kelvin and Luggie (Table 1; $p<0.01$). Differences in diet among the three populations can be seen in Figure 2. *Asellus* formed a major component of the diet in sticklebacks from the River Luggie (average occurrence per sample, 36%) and River Kelvin (29%). In contrast, *Asellus* and *Gammarus* occurred relatively infrequently in fish from the Aurs Burn (7%). Copepods were found most frequently in fish from the River Kelvin (23%), but were also common in those from the River Luggie (15%) and the Aurs Burn (17%). On the other hand, dipteran larvae were relatively more common in fish from the Aurs Burn (29%), compared to those from the Rivers Luggie (25%) and Kelvin (15%).

Other components of the diet of fish from the River Kelvin and the Aurs Burn were absent from fish from the River Luggie, namely invertebrate eggs and, in the summer months, molluscs. Stickleback eggs were found at low frequencies (never more than 4%) in the stomachs of fish from the River Kelvin and the Aurs Burn, but these too were completely absent from fish caught in the River Luggie. In contrast, ephemeropterans were never found in the stomachs of sticklebacks from the Kelvin, but these did occur in those from the Aurs Burn (8%) and the River Luggie (1%).

Figure 1.

The diet of Three-spined Sticklebacks. Combined data from all three study sites in two-month sampling periods from October 1983 to August 1984.

(a) Percentage stomach fullness (graph) and proportion of fish with empty stomachs (histogram).

(b-f) The proportion of fish whose stomachs contained some common prey items.

(b) *Asellus*

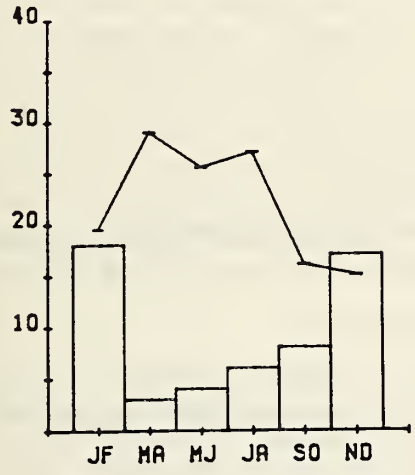
(c) Copepods

(d) Dipteran larvae

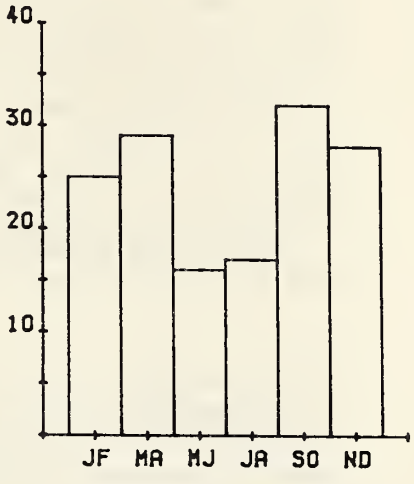
(e) Ephemeropterans

(f) Molluscs

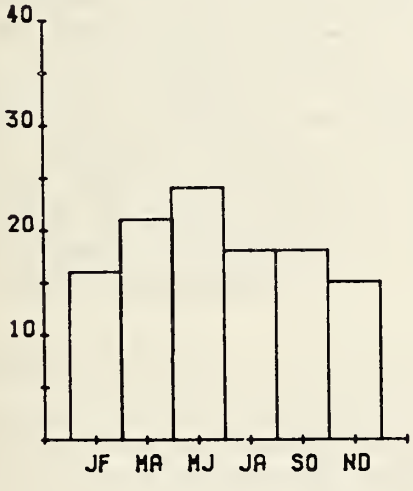
a. Stomach fulness



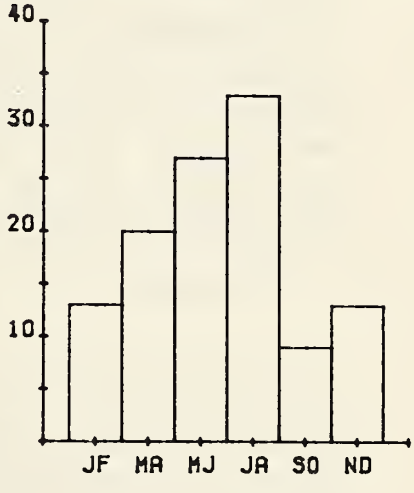
b. Asellus



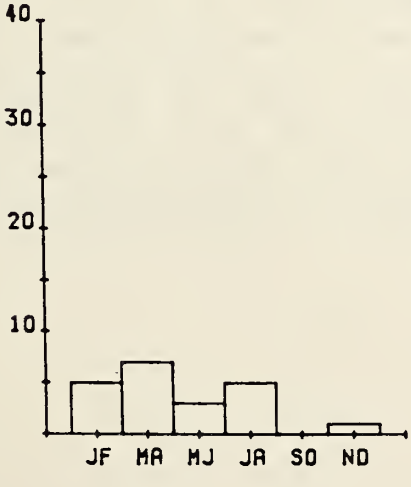
c. Copepods



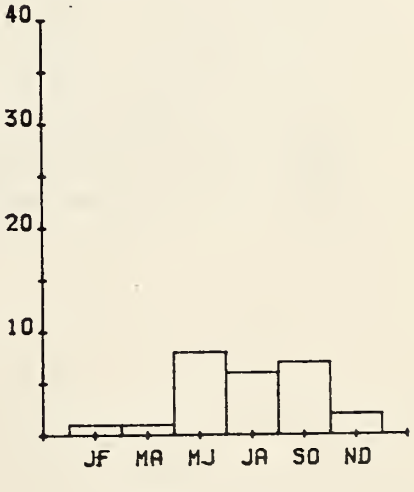
d. Dipterans



e. Ephemeropterans



f. Molluscs



Time of year

Time of year

Table 1.

Means and standard error of percentage stomach fullness for the populations showing those with significant differences

Population	Sex	Percentage Stomach Fullness
Kelvin	Female	53 ± 3 ---------]
Luggie	Female	48 ± 3 ----]] **] **
Aurs Burn	Female	37 ± 3 ----]----]
Kelvin	Male	52 ± 4 ---------]
Luggie	Male	43 ± 3 ----]] **] **
Aurs Burn	Male	28 ± 3 ----]----]

** = P <0.01

GENDER EFFECTS

There were no significant differences between females and males in percentage stomach fullness, although this was consistently lower for males (see Table 1) and broadly speaking their diets were very similar. However, some differences in diet were observed consistently across populations. In particular, ephemeropterans ($p<0.05$) and molluscs ($p<0.05$) occurred more commonly in females than in males. In the case of molluscs, this effect was particularly marked during the period from April to July.

SIZE EFFECTS

Figure 2 shows stomach fullness and diet composition in the three size categories of fish for the months of December to March, when overall feeding patterns were broadly comparable (to avoid confounding the effects of size with season). There were no differences among the size groups in stomach fullness, but consistent changes in diet were observed. The proportion of fish eating *Asellus* increased significantly with size in the Rivers Luggie and Kelvin ($p<0.01$). The occurrence of this prey type was consistently lower in Aurs Burn fish, which instead seemed to be taking dipterans at all sizes. The occurrence of plant material increased with size ($p<0.01$), perhaps reflecting a shift to a benthic diet. In sticklebacks from the River Kelvin, smaller fish took significantly more copepods and dipterans than did larger fish. Stomachs of fish of all sizes from the River Luggie were more likely to contain *Asellus* than those of their contemporaries from other sites, while copepods were relatively uncommon.

Discussion

Except for the absence of cladocerans, the range of prey items found in the diet of the fish in this study is in broad agreement with information already published on the feeding habits of sticklebacks (Hynes 1950, Maitland 1965, Mann and Orr 1969, Manzer 1976, Allen and Wootton 1984). The diet of the fish from the Aurs Burn, with dipterans and copepods the dominant prey type, is most comparable to that described in earlier studies. The high frequency of fish with *Asellus* in their stomachs reported in the Rivers Luggie and Kelvin is unusual for 'leiurus' fish, making their diet comparable to that described by Larson (1976) for the benthic form of stickleback in Paxton Lake, British Columbia. The differences in diet among the three study populations could be the result either of differences in availability or accessibility of prey types, or of differences in prey selection.

Figure 2.

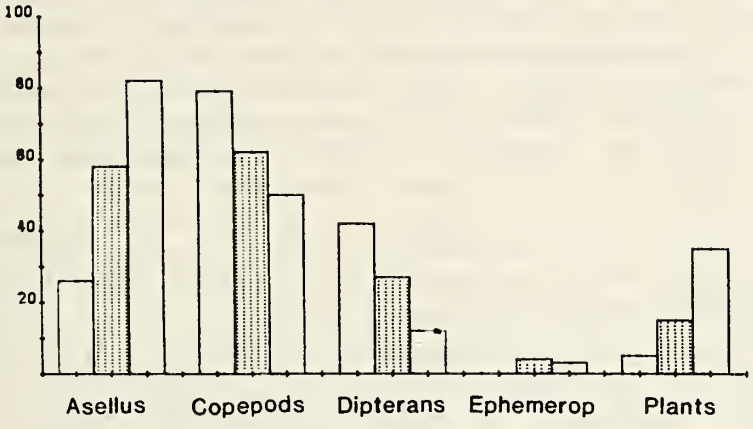
The occurrence of some common prey items in sticklebacks of three size categories in the three study populations. Data are from December 1983 to March 1984.

First column: <29mm.

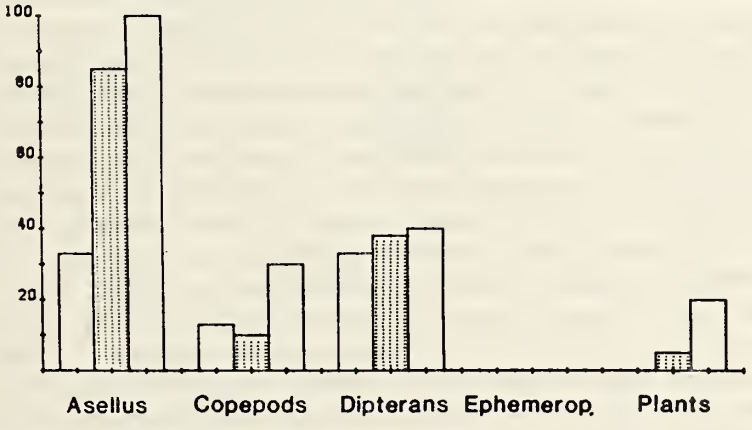
Second column (dotted): 30-45mm.

Third column: >46mm.

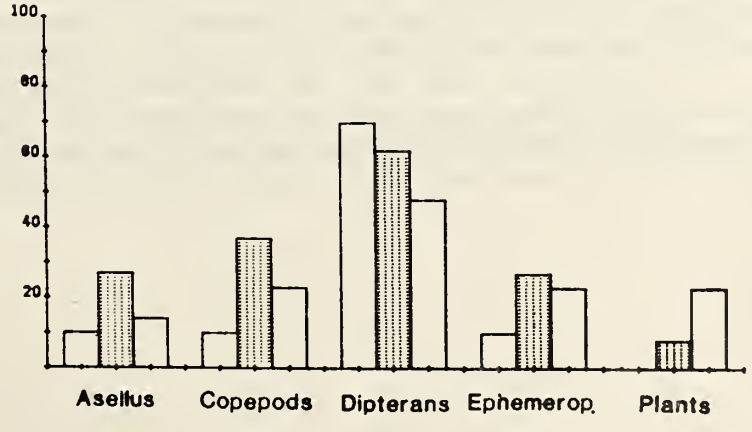
a. River Kelvin



b. River Luggie



c. Aurs Burn



The seasonal changes in stomach fullness and diet composition reported here (with highest levels of stomach fullness and a predominance of copepods in spring and early summer) also confirm previous studies. Such seasonal changes in diet are usually interpreted as the result of changes in prey availability (Manzer 1976). The fact that *Asellus* occurred in the diet most commonly in the winter, when the fish had relatively low stomach fullness, suggests that *Asellus* is a less preferred prey type, taken when other items were not available. The occurrence of plant material in the diet generally varied in parallel with the occurrence of *Asellus*, thus suggesting that the fish may ingest plant material while foraging in the benthos.

Male and females showed equivalent stomach fullness levels all the year round, including the summer when levels were slightly decreased in both sexes. There were some minor differences in diet, including a higher incidence of Ephemeroptera in females (in the two sites in which this prey type was found), and a higher frequency of molluscs in the diet of breeding females. The latter may reflect a response special to nutritional requirements, comparable to that described in birds during egg production (see Houston 1978).

The low frequency of large prey items such as *Asellus* in the diet of small fish (especially those from the River Kelvin and the Aurs Burn) also confirms previous findings (e.g. Manzer 1976). Measures of handling times and calorific contents suggest that even small *Asellus* are unprofitable prey for small sticklebacks; zooplankton and chironomid larvae are more profitable. In contrast, small and medium *Asellus* are profitable prey for larger sticklebacks (Ibrahim 1988). The differences in diet in fish of different ages from the Rivers Kelvin and Luggie may, therefore, reflect the changing profitability of the available prey items. It may be that alternative small prey are in short supply in the River Luggie. This would account both for the higher percentage of *Asellus* in the stomachs and for the slower rates of growth (Ukegbu 1986).

Summary

Stomach fullness and diet composition were studied in Three-spined Sticklebacks from three sites in south-west Scotland over a one year period. The range of prey items taken was broadly comparable to that described in previous studies. However, sticklebacks from two of the three study sites were taking a larger proportion of benthic prey than had usually been reported. Feeding patterns varied with season, stomach fullness and the occurrence of copepods being greatest in the

late spring and early summer. Males and females had broadly comparable feeding patterns, although females tended to take more ephemeropterans and, during the breeding season, more molluscs. Large prey items, such as *Asellus*, were relatively uncommon in the stomachs of smaller sticklebacks, which contained relatively higher levels of copepods and dipteran larvae. These are more profitable prey types for small fish, and in one study population low availability of smaller prey items may be compromising growth.

Acknowledgements

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"...LIGHT ON OBSCURE OCEANOGRAPHICAL PROBLEMS"; AN HISTORICAL REVIEW OF STUDIES OF THE PHYSICS OF LOCH NESS

By S.A. THORPE
Department of Oceanography,
University of Southampton

Early References and Depth Soundings

That a study of the physics of Loch Ness might hold some surprises was apparent fourteen hundred years ago. Adamnan [Adamnain or Adomnan], ninth Abbot of the monastery of Iona from 679 until his death in 704, in his Life of Saint Columba (*Vita Sancti Columbae,* c.690), told how the Saint was having trouble with the local magicians: "On the appointed day as he had intended the Saint came to the long lake of the river Ness, followed by a large crowd. Then the magicians began to exalt, because they saw a great mist brought up, and a stormy adverse wind ... so our Columba, seeing that the elements were being roused to fury against him, called upon Christ the Lord. He entered the boat, and while the sailors hesitated, he himself, more steadfast, ordered the sail to be raised against the wind. When this was done, and with the whole crowd looking on, the ship moved with extraordinary speed, sailing against the contrary wind" (Anderson and Anderson, 1961). Myth or legend, I will come later to the relevance, and perhaps an explanation, of this strange report.

Columba died in 597 and Adamnan wrote nearly a hundred years later. There followed a thousand years from which I have found no records bearing on the physics of Loch Ness, but by the mid-eighteenth century some important features were well known. These are recorded on two charts made by Joseph Avery around 1730. What appears to be the earlier is a Board of Ordnance plan presently kept in the Scottish National Library; this gives thirteen soundings which found bottom in the Loch and four which did not, three of these being at 200 fathoms and well beyond what we now know to be the actual depth. The second chart, from surveys begun in 1725 and continued to 1730, is in the Inverness Museum and Art Gallery. It was prepared by Avery on behalf of the York Building Company, and shows the

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Read to the 1985 Summer Meeting Symposium of the Royal Meteorological Society on 'The History of Meteorology and Oceanography in Scotland'.

boundaries of woods and lands purchased by the Company for the carrying on of iron manufacture; surprisingly, it also gives 85 soundings, the majority close to presently accepted values.

It was thus known that Loch Ness was of remarkable depth, deeper indeed than the water of the nearby Moray Firth; in fact, of all the lakes in the British Isles only Loch Morar is deeper. Moreover, the second of Avery's charts is marked "Loch Ness never known to Friese or have ice upon it". The reason why seems not to have been understood at the time. Dr. Samuel Johnson, in the description of his *Journey to the Western Islands of Scotland,* made in 1773, reported, although not without scepticism, the belief that "Lough Ness is open in the hardest winters", and suggested that if "the fact be justly stated" it must be either because the loch was "sheltered by its high banks from the cold blasts, and exposed only to those winds which have more power to agitate than congeal; or it is kept in perpetual motion by the rush of streams from the rocks that inclose it". At that time it was supposed that the loch was partly supplied "by springs at the bottom", as well as by "the torrents which fall into it on either side". Dr. Johnson also suggested that the great depth, "in some places a hundred and forty fathom deep, a profundity scarcely credible, and which probably those that relate it have never sounded", could play little role in preventing freezing, and commented "for though deep wells are not frozen, because their water is secluded from the external air, yet where a wide surface is exposed to the full influence of a freezing atmosphere, I know not why the depth should keep it open" (Johnson, 1775).

The absence of ice in Loch Ness was clearly a great puzzle, and misinterpretation of the cause had practical consequences. E.M. Wedderburn, of whom more later, spoke of "One boatman, wishing to keep his boat from getting dry while laid up for the winter, filled it with Loch Ness water. The result was not what he anticipated, for the water in the boat froze solid, and burst his boat to pieces" (*B.S.* p.141) (Note 1).

Dr. Johnson added in his narrative that "Natural philosophy is now one of the favourite studies of the Scottish nation" and made the valuable suggestion "and Lough Ness well deserves to be diligently examined". As we shall see, it was over a hundred years before this study was taken up.

A further early reference to the great depth of the loch and to a further physical phenomenon, the surface seiche, was made in a letter written by Mr. Robert Gardener from Fort Augustus to Dr. John Stevenson, a physician at Edinburgh, on 22nd December 1755, following the Great Earthquake which

devastated Lisbon on 1st November of that year. This letter is of such intrinsic interest that it is worth quoting at some length. Gardener (1755) wrote:

"I arrived at Fort-Augustus, from Fort-William, on the 31st of October last: next morning about ten I walk'd abroad, when the barrack-master, and several others, came and acquainted me, that they had seen a very extraordinary agitation of the waters at Loch Ness. I refused giving credit to their story, and a little afterward returned to the fort.

About 11, my clerk and the brewer at the place came and acquainted me, that a more extraordinary agitation than the former had happened, and they apprehended some danger to our brewery, which is situated where the river Oich discharges itself into the lake. I walked then to that place, but before my arrival the water had returned to its usual channel. I saw very clearly the marks on the banks, to which it had flowed; the banks were quite wet, and a strip of leaves of trees and twigs etc. left on them. I inquired then into this affair, and the account the spectators gave were, that they observed the river Oich, which runs from west into the head of the lake, swell very much, and flow up the river from the lake, with a pretty high wave, about two or three feet higher than the ordinary surface, with a pretty quick motion against the wind, and a rapid stream, about two hundred yards up the river; then broke on a shallow, and flowed about three or four feet on the banks on the north side of the river, and returned again gently to the lake. That it continued ebbing and flowing in that manner for about an hour, without any waves so remarkable as the first, till about 11 o'clock, when a wave higher than any of the rest came up the river, and, to the great surprize of all the spectators, broke with so much force on the low ground, on the north side of the river, as to run upon the grass upwards of thirty feet from the river's bank.

Loch Ness is about twenty miles in length, and from one to one and a half mile broad; bears from south-west to north-east. There was no extraordinary muddiness observed in the water, though it did not appear quite so clear as usual. The morning was cold and gloomy, and a pretty brisk gale of wind blowed from west south-west. The river Oich lies on the north side of the fort, and on the south side runs the river Tarff from west south-west, discharging itself also into the head of the lake; and which was observed to be agitated at the same time and manner as the other. But there were no shakings or tremors felt upon the land. I have heard of the same agitations in Loch Lommond. It is probable all the other

lakes in the highlands were also agitated, and it is my opinion they were, though I have not heard of many particulars".

Gardener added a post-script: "Loch Ness is vastly deep, its soundings in many places being from 100 to 135 fathom, which is greatly below the level of the sea at Inverness. Its sides are most part rocky, and it deepens immediately from them. About three musket-shot from the river Oich it measures about 120 fathom in depth". I am told by the British Museum that one musket shot was between 50 and 100 yards, but perhaps it represented a more exact distance at that time.

Gardener also mentioned that the phenomena were witnessed by "Mr. Gwyn, son of Captain Gwyn, of the Loch Ness Galley". For at least 79 years from about 1727 the Gwyn (Gwynn or Gwynne) family provided commanders for the military galleys which supplied the Fort (Note 2), wearing out at least six vessels according to the *Third Annual Report* of the 'Commissioners for making an Inland Navigation commonly called the Caledonian Canal' (published in the House of Commons Sessional Papers for 1806). One of the family, Captain Mark Gwynn, made soundings for Thomas Telford in about 1802 during the survey for the Canal (Rolt, 1979; James Watt had conducted an earlier survey for a canal but I have found no record that any soundings were made). Gwynn was also paid £35:14:0d. for keeping daily records of winds and weather at Fort Augustus for six years, part of a continuous sequence lasting from 25th September 1804 to 30th April 1821 which was published in the Commissioners' Reports. Also published in the early Reports were surveys by Murdoch Downie and John Howell in 1803-04 which included some fifty soundings in the Loch.

Downie wrote in a letter to Telford on 9th December 1802 (*2nd Annual Report*) "as there is no tide or current, or any hidden danger in it" [Loch Ness]...."no particular direction (different from those always in life) can be given to ships navigating it, except that of keeping nearest the Lee Shore, when squalls appear upon the Loch". In fact there are currents, but these are not permanent.

The Canal was completed from the Moray Firth as far as Fort Augustus in summer 1818, thus allowing shipping to enter Loch Ness from the sea, and the full length of the canal, providing passage from the Moray Firth to Loch Linnhe, was opened on 24th October 1822. The level of the loch was raised between 1843 and 1847, when the weir at Dochgarroch was extended during extensive repairs to the Canal.

Bathymetrical Survey of the Scottish Fresh-Water Lochs

We now come to the scientific studies of Loch Ness. The first observations on the temperatures of Scottish lochs were made in 1812 and 1814, when Mr. James Jardine carried out a series of observations at different depths in Loch Tay, Loch Katrine and Loch Lomond. Although not actually published by Jardine himself, the results were later described by Sir John Leslie (1838). Jardine's observations stood "by themselves in Scotland for a period of nearly sixty years" (*B.A.* p.92) until Sir Robert Christison's work in these same three lochs during 1870 and 1871 (Christison, 1872). The work of Jardine and Christison was examined and compared, and certain conclusions drawn, by Dr. A. Buchan (1872). Some years later "perhaps the most important contribution to the literature of the subject during last century was Sir John Murray's paper, published in 1888, on the effect of winds on the distribution of temperature in the sea and fresh-water lochs of the West of Scotland" (*B.A.* p.93).

It was not until the present century, however, that systematic measurements of physical variables were made in Loch Ness. These proved to be of such importance to physical limnology, and perhaps also to oceanography, that it is worth briefly explaining how they came about.

To make a bathymetrical survey of all the fresh-water lochs of Scotland was Sir John Murray's idea. Murray had made excursions into the fresh-water lochs in the Caledonian Canal whilst studying the Scottish sea lochs between 1884 and 1891. He noticed the striking differences in physical and biological conditions between the fresh and sea-water lochs, notably those connected with freezing and the absence of phosphorescence in fresh-water organisms, and recognised the value of comparative studies. His interest in the fresh-water lochs, however, appears to have been awakened earlier, for during 1883 and 1884 he persuaded the Councils of the Royal Societies of both London and Edinburgh to consider the merit of scientific studies in the Scottish fresh-water lochs, and both Societies made strong representations to the Government, urging that a bathymetrical survey should be made. The reply was subtle, indeed shrewd, to the effect that "a survey of the kind indicated did not come within the functions of the Admiralty, which only undertook work in the interests of navigation, nor of the Survey Department of the Office of Works (late Ordnance Survey), which limited its operations to the dry land, and that, however interesting from the scientific point of view, their Lordships were unable to sanction the proposed surveys" (*B.A.* pp.3-4).

Murray and Mr. J.Y. Buchanan made soundings in Loch Ness

in 1888, but it was not until 1897 that, still without Government support, Murray and a "young friend", Mr. Frederick P. Pullar, began a regular programme of surveys, although still regarding it "as a holiday task" (*B.S.* p.4). According to a local journal, in 1899 Murray was still of the opinion that "the work ought to have been done by Government", suggesting "that it was as necessary to know the depth of a loch as the height of a mountain" (Note 3).

The work continued steadily, two papers being prepared on the results, until tragedy happened. On 15th February 1901, Frederick Pullar, only 25 years old, lost his life whilst trying to save one of several fellow skaters who had fallen through the ice at Airthrey Loch. This brought the survey work to a halt, and it was Murray's intention to abandon it altogether. Mr. Laurence Pullar, father of Frederick Pullar, however, was determined to see his son's work continued, himself to take his son's place so far as possible and, what was more important, to put the Survey on a secure financial base. The Royal Societies and the British Association (see *Times,* 18th September 1901) endorsed the importance of the scientific work, and a trust was established by Laurence Pullar to support the Survey. Even the Government began to show some interest. Murray received a letter from the Director-General of the Ordnance Survey stating that the "Board of Agriculture had sanctioned the issue to the staff of the survey of two copies of the 6-inch and one copy of the 1-inch maps of the districts in which lakes were situated, one copy of the former to be returned to the department with the depths of the lakes laid down on it, with a view to the lake-contours being shown on the Ordnance Survey maps" (*B.S.* p.7. Murray's low regard for the administrators is thinly veiled in making this direct quotation from the letter). Tracings of the maps with soundings marked on them were returned to the Ordnance Survey Office as the work proceeded, for safe keeping and reference (Note 4). (The Ordnance Survey informs me that the original tracings cannot now be found; perhaps they were lost with other archive material in the bombing during the last war). Help was also promised from the Hydrographer, and the Geological Survey provided maps and assistance.

On the recruitment of staff for the Survey, Dr. H.R. Mill, then President of the Geographical Section of the British Association, was reported in the *Times* of Friday 13th September 1901 as follows: "Sir John Murray and Mr. Laurence Pullar wished to meet 3 or 4 capable young fellows" (a chemist, a geologist, a botanist and a zoologist). "When found, they would be offered a salary sufficient to enable them to give their whole time to the work, but not large enough to induce anyone

who had not the love of science at heart to take it up". He "could promise those who would have the good fortune to be selected plenty of hard work for which they would get the fullest credit" and "scientific and intellectual training such as even the Universities did not afford". With a permanent staff of seven, and numerous temporary assistants, the Survey began in earnest in 1902.

The scientific reports of the Survey make fascinating reading (Murray and Pullar, 1910). They contain touches of whimsical narrative and occasional illuminating phrases which reveal the scale and problems of the investigation. Frederick Pullar himself designed a sounding machine (Note 5) which could not only be attached easily to a rowing-boat but which could be carried "on a bicycle", presumably a great help when visiting remote lochs. The work of the Survey relied heavily on the "Courtesy and assistance rendered by Scottish proprietors in the loan of boats" and "without their cooperation the work could not have proceeded". "In some few cases the surveyors were looked on with a little suspicion, but the great majority of proprietors took a lively and intelligent interest in the survey. It was rather amusing at times to observe the result of the soundings on the inhabitants of districts in which the lochs are situated. As a rule, lochs, or some parts of a loch, are regarded as very deep or without bottom. When a loch with this reputation was found to be relatively shallow, the result would be questioned, and a feeling of affront or injury prevailed among the inhabitants" (*B.S.* p.10). Fixing the positions of survey points in a loch proved difficult. It was found that "the most accurate method was to take the soundings as quickly as possible while rowing across the lochs from one point to another". The boatmen, and several helped in the survey, were first 'calibrated' (my quotation marks), i.e. "Before making a section across a loch, the boatman was trained for some time to ascertain the distance covered in ten, fifteen, twenty, and fifty strokes with the oars" (*B.S.* p.14).

The principal work of the Survey was, of course, concerned with the determination of the depth of the lakes, and over 1400 soundings were made in Loch Ness alone, but the work extended into other branches of the science of limnology: lake geology, chemistry, biology and physics. In reading the Survey's reports, one is struck by the high level of scientific communication of those days and with the breadth of the investigation. The Survey was in close touch with limnologists in Germany and Switzerland, notably Professor F.A. Forel. At the request of C.T.R. Wilson, Mr. E.R. Watson (1904b) carried out a study of the electrical conductivity of air in containers lowered into Loch Ness. One of Pullar's sounding machines (Note

6) was sent to Robert Peary in 1905 for use in his Arctic expeditions. Seiches, currents, temperatures and ice formation were studied by the Survey. Mirages are commonly seen in Loch Ness and were carefully reported. Clearly here was a group of people, partly amateur, but all very conscious of, and curious about, their surroundings, dedicated to understanding the environment by careful observation and scientific measurement.

It would be quite wrong to think that Loch Ness was the centre of effort of the Survey. Altogether 562 lochs were surveyed, 250 in the peak year of 1903. Surface seiches were most intensively studied in Loch Earn by Professor George Chrystal, following earlier work at Fort Augustus in Loch Ness beginning in June 1903, and in Loch Treig where what was claimed to be the "first authentic seiche recorded in Scotland" (*B.S.* p.17) was observed by the Survey in May 1902.

It was in Loch Ness, however, that one of the most exciting and historic discoveries was made, that of the temperature seiche, and since I have had some personal interest in this phenomenon, the work which relates to it is here described in greater detail than other studies by the Survey.

The Temperature Seiche; E.R. Watson and E.M. Wedderburn

Credit for the original discovery must go to E.R. Watson, who published the definitive paper (1904a) after studies in Loch Ness in 1903, but after Watson left Scotland in January 1904 to take up a professorship at Calcutta (he became Professor of Chemistry in Libpur C.E. College), the labour of the collection and analysis of much of the data which confirmed the theory was undertaken by Mr. E.M. Wedderburn, work which was reported in his paper in 1907(a).

Wedderburn had been attracted to geophysical studies by Chrystal whilst a student at Edinburgh University, and helped in the observations of surface seiches in 1903 (Note 6). Temperature measurements were started in Loch Ness in July 1903 following a bathymetrical survey begun on 2nd April of that year. Temperatures were observed at about ten depths using reversing thermometers, at first on roughly a daily basis near Fort Augustus, and later two or three times a day at stations along the Loch visited by the steam launch *Sunbeam*. In September 1903 a more sophisticated method was tried. The yacht *Rhoda* was anchored in 250 feet of water off Fort Augustus, and was equipped with platinum resistance thermometers which could be lowered from the yacht and connected by cable to a recorder housed on shore in the Abbey boathouse. This "elaborate and costly apparatus did not come up to our expectations" Wedderburn (1907a), but the use of the yacht as a fixed

platform proved to be of great value. Daily records of temperature, both at the surface and at about 250 feet, were continued throughout the winter of 1903-04, and in August 1904 observations were made at ten levels every two hours. The peak of activity was reached in September 1904, when stations at Fort Augustus, Invermorriston, Inverfarigaig and Dores were occupied simultaneously at 6.00 a.m., 12.00 noon, and 6.00 p.m. each day. The daily measurements from *Rhoda* were continued with the assistance of monks of the Order of Saint Benedict at Fort Augustus from October to April 1905 (Note 7).

All this data enabled Wedderburn to define the seasonal changes of temperature and heat content of the loch, to examine the effect of wind on the circulation, and to establish firmly the existence of the temperature seiche. The seasonal variation of heat content, connected with the formation and destruction of a thermocline, (Wedderburn referred to it using the Germanic '*Sprungschicht*'), amounted to 1.9×10^{16} gram calories compared with the total annual supply of 7.2×10^{16} gram calories (Wedderburn 1907a, p.420). Wedderburn was much interested in "convection currents". He seems to have envisaged changes in thermal structure to be dominated by horizontal (or isopycnal), rather than by vertical, effects, with warmed or cooled water spreading under gravity from the sides of the Loch. The rapid changes recorded by the platinum resistance thermometers were thought to be connected to this mechanism, but he also clearly recognised the existence of what we now know as temperature fine-structure, some sixty years before attention was drawn to its importance in the ocean. "Everything goes to show that heat is communicated from one part of the loch to another by convection more than in any other way (leaving out of consideration the effects of winds)... Another fact which strengthens this view is that there are frequently lesser *Sprungschichts* at different depths, and in the neighbourhood of all these there must be convection currents set up. The behaviour of water in the neighbourhood of a *Sprungschicht* is very similar to the behaviour of water near the surface. Before this was understood, the observers were often puzzled when working with mercury thermometers by obtaining readings which seemed to show the presence of very marked inverse stratification, which always disappeared in a very illusory fashion when any attempt was made to follow it up". Wedderburn added "Such rapid variations are quite natural, as convection currents must inevitably be set up where there are two layers of water of different temperatures in contact with one another, especially so in this case, as, owing to the presence of the temperature seiche, there is relative motion between the two layers" (Wedderburn 1907a, p.430). The meaning here is somewhat

enigmatic, but gives a strong hint that Kelvin-Helmholtz instability and billow turbulence was envisaged. Wedderburn's meaning is much more explicit in a later paper (1911) where he referred to the temperature seiche producing "rapid currents both in the upper and lower layers" [i.e. above and below the thermocline], "the currents in the two layers being opposite in direction and therefore their relative velocity will be very large. Vortices are certain to be caused at the discontinuity where one current slips over another".

The presence of a temperature seiche was best marked by the regular fluctuations seen at Fort Augustus, but was also apparent in the opposite phases of temperature fluctuations at fixed depths at the two ends of the Loch recorded during the intensive phase of measurements in September 1904. Wedderburn remarked that "most of the disturbance which is shown on the Inverfarigaig [half-way along the Loch] curve would seem to be due to a binodal seiche of approximately half the period of the fundamental '(uninodal)' seiche, which, from these curves, appears to be about two days".

This was the first observation of internal waves in natural bodies of water, and it prompted some opposition. Wedderburn had to work hard to convince other limnologists: Professor Halbfass "was of the opinion that the peculiar character of our lakes - the deep valleys in which they are usually situated and their steep shores - made it dangerous and unwarrantable to generalise from our observations. At the same time an attack was made on our theory by Professor E.A. Birge, Wisconsin, U.S.A. who thought that the oscillations observed in Loch Ness might quite well be explained by reference to meteorological conditions. Observations made by Dr. Exner in the Wolfgansee had shown the existence of a temperature seiche there, but the evidence afforded by these observations was not altogether convincing to Professor Halbfass. The author therefore suggested to him that a joint expedition should be made in July and August to a lake of his choosing, and observations made according to the methods used by the Scottish Lake Survey. Professor Halbfass at once fell in with this suggestion, and his choice of a lake was the Madusee in Hinter Pommern" (Wedderburn, 1911). The observations by the joint expedition showed conclusively the existence of the temperature seiche.

Clearly following the line of development of Chrystal's earlier studies on the surface seiche, in which he had helped, Wedderburn made laboratory studies of the temperature seiche (1907b). He and Mr. William Watson also made observations of currents in Loch Ness using an Ekman current meter, although

not without difficulty. Wedderburn anchored a buoy with two hemp ropes in a depth of 700 feet near Invermorriston, suspending the meter from it, or using it as a mooring for a boat from which he could lower the meter. However "Even in a moderate breeze the waves in Loch Ness are of considerable size, and in a small rowing boat it was found very difficult and not a little dangerous to observe in the centre of the lake. The observations were put a stop to for a time by the loss, in some unexplained manner, of the compass box; and during the interval which occurred before the lost box could be replaced the buoy broke from its moorings and took a journey of some sixteen miles, leaving about 2000 feet of rope at the bottom of Loch Ness" (Wedderburn and Watson, 1909). The existence of a wind-driven circulation was established, currents flowing against the wind being found close to the surface in the more-sheltered Invermorriston Bay when the observations were continued, but the currents in Loch Ness proved to be too complex and difficult to observe, and Wedderburn's work on lake circulation was transferred to Lochs Garry (1909,1910) and Earn (1912,1915) which are smaller and in which observations were more easily made.

Wedderburn speculated thoughtfully on the similarities and differences between lakes and oceans (1911), suggesting that Dr. Otto Pettersson's temperature measurements made during the 1890s in the Gudemanfjord might be interpreted in terms of seiches, and called for more observations of temperature variability in the ocean. One idea which has not been found acceptable was that the viscosity of water might be as important as the difference in density in determining lake circulation; the suggestion that warmer, less viscous, and hence "mobile liquid resting on a relatively viscous liquid" gave a tendency "to confine wind-produced currents to water above the discontinuity" (*B.S.* p.143) is now regarded as insignificant - the appropriate Reynolds numbers are far too large for this effect to be very great.

The most sophisticated mathematical treatments inspired by the Survey at the time were undoubtedly Chrystal's (1905; *B.S.* pp. 29-90) studies of surface seiches in basins of different shapes, but the investigations having the most profound influence on oceanography and modern limnology were surely Wedderburn's. It was he who showed the greatest drive and, above all, enthusiasm, and who emerges as the central figure in this review. It is appropriate that recently Wedderburn's name has been suggested to denote a parameter which classifies the deepening of a lake epilimnion by wind (Thompson and Imberger, 1980). Wedderburn was elected a Fellow of the Royal Society of Edinburgh in 1907 when only 23 years old. He was Honorary

Secretary of the Scottish Meteorological Society when it amalgamated with the Royal Meteorological Society in 1921, and all his life he retained an active interest in natural science, although it was for singular services to his Scottish legal profession that he was knighted. He died in 1958 (see Note 8).

Later Observations: C.H. Mortimer

In their Preface to the six-volume final report of the Survey's results, written from the Challenger Office in Edinburgh and published in February 1910, Murray and Laurence Pullar correctly claimed that "Some of the observations....throw much light on obscure oceanographical problems", and that "Most of the observations could, with advantage, have been carried further, by means of improved instruments and methods suggested during the progress of the work". It is clear that they had in mind the successful research in Loch Ness, for they specifically mentioned the temperature seiche. It is a great pity that the idea of learning about the ocean by comparative studies in lakes was not pursued more actively in later years. Limnology was at the brink of becoming a major environmental science. Perhaps it was too inexpensive ever to reach a higher status. Its secondary role is clear enough, at least by implication, in a surprisingly cynical footnote written by Chrystal calling for observations of wave groups: "Sailors have many opportunities for such observations; and physicists might devote some attention to the matter, when they take an open-air vacation from the ardent pursuit of the electron" (*B.S.* p.88). Had the loch observations been continued as Murray and Pullar proposed, it is probable that, with considerable saving, several of the now pressing problems of oceanography and even of fundamental fluid dynamics, notably those concerning turbulent mixing in stratified fluids, the physics of benthic boundary layers and upper ocean processes, would long ago have been recognised and solved.

Perhaps the further investigations to which Murray and Pullar alluded might have been continued, had not Sir John died in a motor car accident in 1914 and the Great War intervened. It was, however, not until 1952 that further measurements were made in Loch Ness. Dr. C.H. Mortimer had recently designed a thermistor chain and used it in Lake Windermere. With support from the Royal Society he brought his instruments to Loch Ness and measured temperatures at Fort Augustus and at two positions in the lake opposite Foyers (Mortimer, 1955). He also passed a rope across the Loch between the moorings at Foyers and, securing a boat to prevent it from drifting, much as Wedderburn and Watson had done, lowered a meter to measure currents.

Mortimer's principal contribution was to recognise the role of the Earth's rotation on the temperature, or internal, seiche which induces a cross-loch tilt of the isotherms, more or less according to Margule's relationship. Mortimer's temperature records from nine depths near Fort Augustus show clearly the periodic fluctuation of the seiche. Surprisingly, however, the rise in temperature occurs very rapidly whilst the fall occurs slowly, and this is not consistent with the idea of a simple uninodal seiche.

Epilogue

Internal waves, first recognised in the waters of Loch Ness, have been extensively studied in the ocean. We now know that Watson and Wedderburn's early notions of the internal seiche of Loch Ness were only partly correct. The wave is rarely a simple uninodal oscillation like a sine wave but is generally highly non-linear, more akin to a shock wave in a gas-filled tube, with an internal hydraulic jump, undular in form, travelling back and forth along the loch thermocline (Thorpe, 1977). It is this which gives rise to the sudden increases in temperature observed by Mortimer near Fort Augustus, for the jump is downward, causing warm near-surface water rapidly to reach levels where previously the water was relatively cold. It also explains the doubling of the frequency near Inverfarigaig, half-way along the Loch, noticed by Wedderburn, for the wave passes here twice for each single arrival at one end.

It seems likely that Wedderburn eventually recognised that the early interpretation was not adequate to explain the measurements. He reported (1907b) observing in his laboratory experiments a "density bore" with the form of a "solitary wave" which was reflected at the ends of the tank. He recognised that a rapid rise in temperature would result if this occurred in the Loch, and advocated making a series of observations half-way along to search for the phenomenon, but unfortunately these were not made. Wedderburn did, however, continue the studies of the temperature seiche in the more regular basin of Loch Earn and later (1915) acknowledged non-linear effects to be important and interpreted some of his measurements in terms of "a travelling bore" which evolved into a steady wave.

What was really important, however, was not the detail, but the idea that internal waves might play a significant role in the dynamics. Science does not necessarily advance by theories, or the interpretation of observations, which are fully correct. What matters is that ideas *are* germinated and hypotheses *are* proposed. Internal waves are now recognised as

being an important naturally-occurring phenomenon in lakes and throughout the ocean.

Finally, to return to St. Columba. Wedderburn had demonstrated how the wind drives a circulation in the Loch which carries subsurface water in a direction contrary to the wind. This counter flow, perhaps because of the Earth's rotation, can reach the surface of the Loch on the northwest side when the wind is strong from the southwest (Thorpe, 1977). Possibly the Saint set out for Iona from the northern end of the Loch in a fierce southwesterly wind, and launched his boat into the unexpected counter-current.

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Miss Margaret Wilkes, Superintendent of the Map Room at the National Library of Scotland, provided information about the early surveys and made several valuable suggestions. Mr. A.D. Cameron, author of *The Caledonian Canal* (1972), provided information about the Gwynn family and drew my attention to the meteorological observations in the Canal Commissioners' Reports. Dr. C.H. Mortimer told me about the 1915 paper by Wedderburn and Young, which I had overlooked. I also received help from the Senior Librarian of the Inverness Public Library, the Curator of the Hydrographic Department, Miss G.L. Beech of the Map Department at the Public Records Office at Kew, and the Executive Secretary of the Royal Society of Edinburgh. Miss Alison Morrison-Low, Curator of the History of Science in the Royal Museum of Scotland, kindly arranged access to material held by the Museum. To all these, and to many other people who gave advice, I express my sincere thanks. Finally, I wish to acknowledge the kindness of the late Rev. L. Downes, particularly for giving me a copy of Adamnan's Life of St. Columba.

Notes

1. Throughout this paper, *B.S.* refers to the pagination of Volume One of the six-volume work by Murray and Pullar (1910); chapters by various contributors, including Sir John Murray, Professor George Crystal, Mr. E.M. Wedderburn, &c.
2. The sad alcoholic fate of "a son of Captain Gwynne of the Government galley" is described in a long footnote by Joseph Mitchell (1883) in *Reminiscences of my Life in the Highlands*. See David and Charles reprint, 1971, Volume 1, pp. 70-71.
3. Interview given to the *Spa Magazine,* No. 8, March 1899, published at Bridge of Allan, in an article entitled 'Our

local celebrity, Sir John Murray'.

4. A file including letters from Murray, correspondence with the Treasury and the Office of Works, and internal O.S. papers about the Survey, is held by the Public Records Office at Kew. Amongst them is a letter from Murray to Colonel D.A. Johnston, Director General, Ordnance Survey, dated 9th October 1901, in which it is clear that it was then Murray's intention to carry out a bathymetrical, physical and biological survey of all the lakes in the United Kingdom.
5. One of these machines is now in the Royal Museum of Scotland in Edinburgh. Unfortunately many of the instruments used by the Survey were destroyed in the late 1940s to make space. The Museum Library holds the original field notebooks (small black books enscribed 'Pullar Trust, Lake Survey' on the cover), as well as volumes of finely drawn temperature profiles, limnographic records, and also notebooks and photographs relating to Wedderburn's subsequent studies in Loch Earn.
6. Murray (*B.S.* p.8) said Mr. E.R. Wedderburn "rendered assistance" to the Survey, although the notice announcing the award of the Makdougall-Brisbane Prize of the Royal Society of Edinburgh to Wedderburn in 1910 (*Proceedings of the Royal Society of Edinburgh,* 31: 705) spoke of his "having been appointed physicist" to the Survey.
7. There now seems to be no record of the Survey's research kept at the Abbey, although the Rev. Fr. Andrew McFillop (pers. comm.) says he remembers Dr. C.H. Mortimer, who used their anemometer records.
8. Obituary notices can be found in the *Quarterly Journal of the Royal Meteorological Society,* 84: 485, the *Meteorological Magazine,* 87: 283-284, and the *Year Book of the Royal Society of Edinburgh 1959/1960,* pp.74-77. Wedderburn was elected a Fellow of the Royal Society of Edinburgh in 1907, becoming Treasurer in 1937.

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